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Relativistic Quantum Molecular Dynamics Simulations of Multi-Strange Particle Production

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The Ultra-relativistic Quantum Molecular Dynamics Model (UrQMD) has been updated and applied to explore rare particle probes in nuclear collisions. Such simulation tools allow to explore the dynamics of the strongly interacting matter (i.e. matter described by Quantum Chromodynamics, QCD). The model was supplemented with novel reaction channels to explore the production of multi-strange particle probes in heavy ion collisions. The extended model has been used for simulations of nuclear collisions at beam energies in the 1-2 GeV/nucleon domain to explore the properties and particle production mechanisms in the dense QCD medium created.

1 Introduction

Quantum Chromodynamics (QCD), sometimes also called the strong interaction is the fundamental theory governing the interactions in the atomic nucleus, i.e. between the protons and neutrons. Also the neutrons and protons themselves are build up from strongly interacting elementary particles, called the quarks and the gluons. While lattice QCD allows to obtain *ab initio* results based on the Lagrangian of QCD, this approach is restricted to static equilibrium conditions and does not allow to model dynamical processes. Unfortunately, dense and hot QCD matter is usually created by the collision of heavy ions, e.g. Gold on Gold collisions, producing a transient state that finally decays into “stable” particles that can be detected by the experiment. Therefore it is necessary to connect the lattice QCD results with a dynamical evolution model of the matter to allow for a comparison with the experimental observables. A well established approach to simulate the evolution of QCD matter is the Ultra-relativistic Quantum Molecular. This model combines relativistic Boltzmann dynamics for the initial and final stages of the reaction with a hydrodynamic model for the hot and dense stages of the reaction. At lower energies, however, a decoupling of the hydrodynamic stage and the Boltzmann phase is not possible and a direct Quantum Molecular Dynamics simulation is employed to integrate the equations of motion. Within the last years the simulations were updated^{1,2} to describe rare channels of multi-strange particle production to gain important insights into the creation mechanisms of these states and the properties of the matter created.

In Sec. 3 the UrQMD model will be introduced and the main modifications will be outlined. Sec. 4 introduces the topic of subthreshold particle production. Finally, Sec. 5 will then discuss the results for the multi-strange particle production and provide a comparison to the HADES data. The paper will finally conclude and provide some outlook.

2 Motivation

QCD matter under extreme conditions is created in today's largest accelerator facilities, namely the Large Hadron Collider (LHC) and the Super Proton Synchrotron (SPS) at CERN. At lower energies, the relativistic heavy ion collider RHIC at Brookhaven allows to explore the energy excitation function of observables, while GSI and FAIR at Darmstadt will map out the low energy and high density regime. The systems created in such collision have a typical life time of 10^{-23} seconds and temperatures above a billion degrees, the densities are similar to those expected in neutron stars. The measured particle spectra generally only allow to reconstruct the emission momenta of the particles and their mass after most of the produced particles have already decayed. A major task is to relate these particle spectra to the properties of the matter, e.g. the temperature and density (the Equation of State), the degrees of freedom during the hottest and densest time and other properties, e.g. viscosities and in-medium spectral functions of hadrons.

Recently two kinds of rare probes have gained a lot of attention in the GSI energy regime: I) multi-strange hadron production, i.e. the production of exotic particles consisting of strange quarks like the Φ meson (a strange-anti-strange state, $s\bar{s}$) or the Ξ baryon, a sss state. II) leptonic probes, here specifically pairs of electrons that are emitted from the reaction zone. The HADES experiment at GSI has recently observed unexpectedly high yields of multi-strange Ξ baryons in Ar+KCl reactions at 1.75 GeV beam energy. This observation could not be explained in terms of statistical models or state-of-the-art transport simulations. A similar situation arose in the recent past with the production of the multi-strange Φ meson in the same energy range. The observed strong enhancement of both hadron species can now be explained and will allow to probe multi-step processes and new production channels as will be detailed below.

A better understanding of strange particle production is not only relevant for elementary particles, but also serves as input for simulations of exotic hyper matter states, e.g. $^{\Lambda}$ He and heavier states³⁻⁵.

3 The UrQMD Model

UrQMD is based on the solution of a coupled set of Boltzmann equations for the time evolution of each hadron species. The main inputs for the simulation are the properties of the individual hadrons supplemented by the interactions cross section. The cross sections are either fitted to available data, calculated from effective models or taken from the additive quark model. Hadron production in the UrQMD transport model^{6,7} proceeds through different channels: The excitation and de-excitation (decay) of hadronic resonances, the excitation and de-excitation of a string and the annihilation of a particle with its anti-particle. Strangeness exchange processes, which can change the flavour content of a hadron are also included¹. The probabilities of the different processes are governed by their reaction cross sections. These cross sections serve as input for the model and are, whenever possible, taken from experimental measurements of elementary (binary) collisions. For example the total and inelastic cross section of binary proton+proton collisions has been measured in many experiments over a wide range of beam energies⁸. The difference between the total and elastic cross section therefore should correspond to the inelastic cross section.

Here again, many different reactions are possible. In UrQMD the inelastic part of the nucleon+nucleon cross section (up to a certain energy) is described by resonance production channels. The possible channels of resonance excitations are divided into several classes:

1. $NN \rightarrow N\Delta_{1232}$
2. $NN \rightarrow NN^*$
3. $NN \rightarrow N\Delta^*$
4. $NN \rightarrow \Delta_{1232}\Delta_{1232}$
5. $NN \rightarrow \Delta_{1232}N^*$
6. $NN \rightarrow \Delta_{1232}\Delta^*$
7. $NN \rightarrow R^*R^*$

Here R^* could be any excited N^* or Δ^* state. Since a large part of the channels are not known, or only measured within a limited energy interval one uses an effective parametrisation of the different cross sections.

4 Sub-Threshold Particle Production

If the centre-of-mass energy of the collision is below the threshold for the production of a certain hadron type, these interaction are called sub-threshold. Sub-threshold collisions are therefore prime testing grounds for multiple interactions. When discussing sub-threshold production of ϕ 's and Ξ 's in nuclear collisions one should note that there are two distinct mechanisms which allow for the production of hadrons with masses, higher than what would be energetically forbidden in elementary reactions:

1. One is the fact that in a nucleus, the nucleons acquire a Fermi momentum due to their bound state. Because of the Fermi momenta, the actual energy of two colliding nucleons will not be exactly the beam energy but a smeared out energy distribution. This allows for collisions of nucleons at energies higher than the actual beam energy.
2. Furthermore energy can be accumulated due to secondary interactions of already excited states, produced earlier in the collision^{9,10}.

As an example for deep sub-threshold production of multi-strange hadrons we will first investigate the production probability of resonance states with sufficiently high mass to produce a ϕ or Ξ in collisions of Ca+Ca (corresponding to the Ar+KCl collisions studied at the HADES experiment). In such collisions, from the Fermi momenta alone, about two percent of all primary $N + N$ collisions will have an invariant mass large enough to produce a ϕ meson, while essentially none has sufficient energy to produce a Ξ . Even though a small fraction of initial collisions has sufficient energy to produce a ϕ , none can be produced at this energy through a string excitation because in the string picture a ϕ can only be created together with a $K + \bar{K}$ pair, increasing the effective threshold for ϕ production by a string fragmentation by an additional 1 GeV.

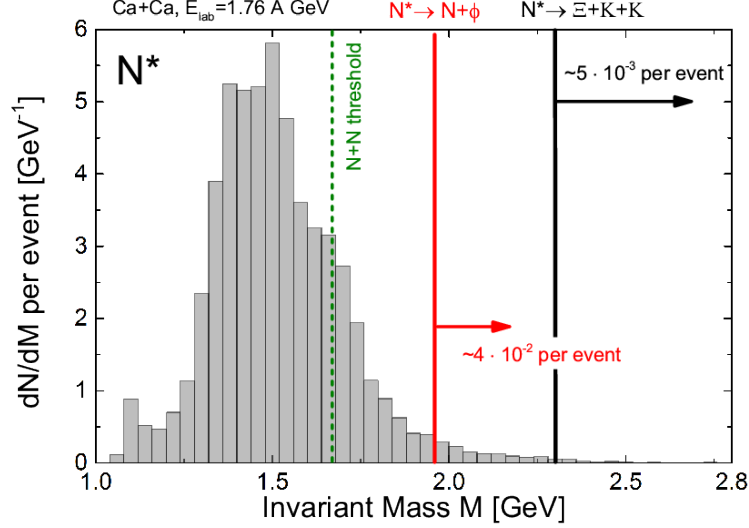


Figure 1. Invariant mass distribution of N^* resonances produced in collisions of Ca+Ca at a fixed target beam energy of $E_{lab} = 1.76$ A GeV. We consider events with an impact parameter smaller than $b < 5$ fm, in accordance with HADES experiment specifications. The vertical green dashed line indicates the maximum mass a N^* can have in an elementary $N + N$ collision at the same beam energy. The vertical red line depicts the ϕ production threshold mass while the black line corresponds to the $\Xi + K + K$ threshold mass².

Fig. 1 shows the calculated invariant mass distributions of N^* baryons produced in Ca+Ca collisions at a fixed target beam energy of $E_{lab} = 1.76$ A GeV and a centrality range of $b < 5$ fm. The vertical green dashed line indicates the maximal N^* mass possible in elementary NN reactions at the same beam energy. It is clear from this figure that a substantial number of N^* resonances with masses larger than the apparent threshold energy is produced in the nuclear collision. We also indicate, as vertical lines, the minimal mass a N^* would need in order to decay into a final state with a ϕ (red line) or even Ξ (black line). From this distribution we conclude that a moderate amount of excited states with sufficiently high mass are available that may produce ϕ mesons as well as Ξ baryons. In the following we explore decays of the most massive N^* resonances implemented in UrQMD, namely the $N^* \rightarrow N + \phi$ and $N^* \rightarrow \Xi + K + K$ channels, in order to describe the production of ϕ and Ξ particles near and below their elementary threshold energies. In particular we will use the $N^*(1990)$, $N^*(2080)$, $N^*(2190)$, $N^*(2220)$ and $N^*(2250)$ states included in the UrQMD model, as their decay channels are experimentally not well constrained and they have a sufficiently large mass.

Using ANKE data¹¹ we find, that a branching fraction of $\frac{\Gamma_{N+\phi}}{\Gamma_{tot}} = 0.2\%$, for all the above mentioned N^* resonances, provides a very good description of the measured ϕ production cross section in proton+proton reactions at ANKE. The new HADES data on Ξ production in p+Nb reactions is used as a proxy for the unavailable elementary collision data to fix the $N^* \rightarrow \Xi + K + K$ branching fraction. To describe the measured production yield of Ξ^- 's we obtain a branching fraction $\frac{\Gamma_{\Xi+K+K}}{\Gamma_{tot}} = 10\%$ for all N^* states mentioned above, that have a sufficiently high mass for this decay.

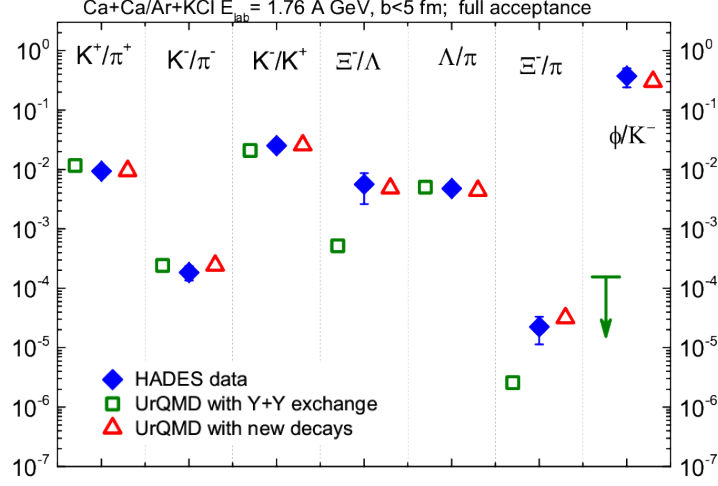


Figure 2. Different strange particle ratios from the UrQMD model in its default settings (green squares), compared to our results including the new N^* decays (red triangles). We compare the simulations for Ca+Ca at $E_{\text{lab}} = 1.76$ A GeV and $b < 5$ fm with published HADES data¹²⁻¹⁵ for Ar+KCl collisions at the same beam energy (blue diamonds)².

5 Comparison to HADES Data

Having constrained the branching fractions, we employ this new mechanism to estimate the production probabilities of ϕ 's and Ξ 's in nuclear collisions, particularly at sub-threshold energies. In Fig. 2 we present results on strange particle ratios, in Ca+Ca collisions at $E_{\text{lab}} = 1.76$ A GeV. The default calculation with the previously released UrQMD version (v3.4) is shown as green squares. Compared to the default calculation we show the new results, including the ϕ and Ξ decay channels of the N^* as red triangles. A considerable increase in the ϕ and Ξ^- production is visible. More importantly when we compare all the obtained strange particle ratios with Ar+KCl data from the HADES experiment (blue diamonds) we observe a very good description of all measured ratios, including the ϕ and Ξ . Such a good description of the full set of data has not been achieved in any previous study. Hence, we conclude that strange particle production in Ar+KCl collisions at the HADES experiment can be explained, and is in fully consistent, with production cross sections obtained in elementary reactions.

In Fig. 3 we present predictions for the same strange particle ratios shown in Fig. 2, in Au+Au reactions at 1.23 A GeV with the new ϕ and Ξ production channels. The red triangles indicate the ratios for Ca+Ca collisions already shown in Fig. 2 for comparison, while the black triangles are the predictions for Au+Au collisions at a beam energy of $E_{\text{lab}} = 1.23$ A GeV and $b < 9.5$ fm. Collisions at this energy have been recently investigated at the HADES experiment. Up to now only preliminary data is available for few particle ratios, shown as blue diamonds. Apparently the preliminary ϕ/K^- ratio seems to indicate a small difference between data and our model study. It will be very interesting to

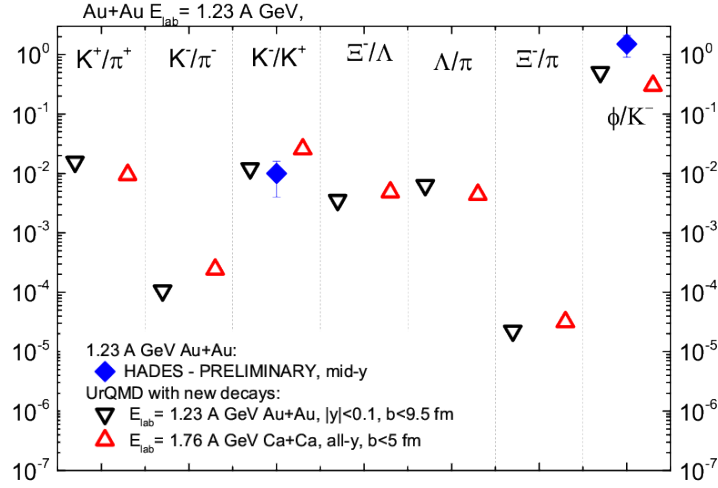


Figure 3. The same particle ratios as in Fig. 2 for Au+Au reactions at $E_{\text{lab}} = 1.23$ A GeV, calculated with the UrQMD model, including the new resonance decays. The red triangles correspond to the results for Ca+Ca, already shown in Fig. 2. Preliminary HADES data¹⁶ is shown as blue diamonds².

see whether this holds for the final data and whether a similar difference will also be seen for the Ξ^-/Λ ratio.

6 Summary

We have implemented novel production channels into the Ultra-relativistic Quantum Molecular Dynamics model. These new channels allow to explain both, the Φ and Ξ production in sub-threshold reactions studied at GSI-HADES. As next steps we aim to explore the implications of these novel channels for further reactions.

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